First ADS analysis of $B^- \to D^0 K^-$ decays in hadron collisions

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for the CDF collaboration

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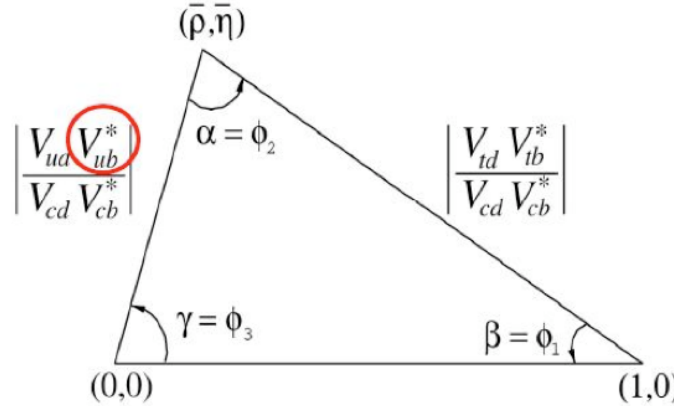
Motivation: CKM γ angle measurement

CKM matrix

CP violation if $\eta \neq 0$

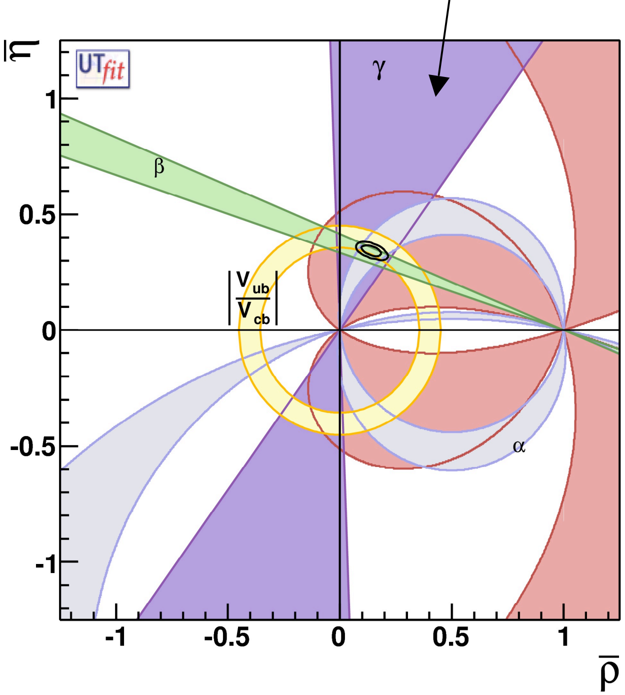
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

b → u transition
B meson system

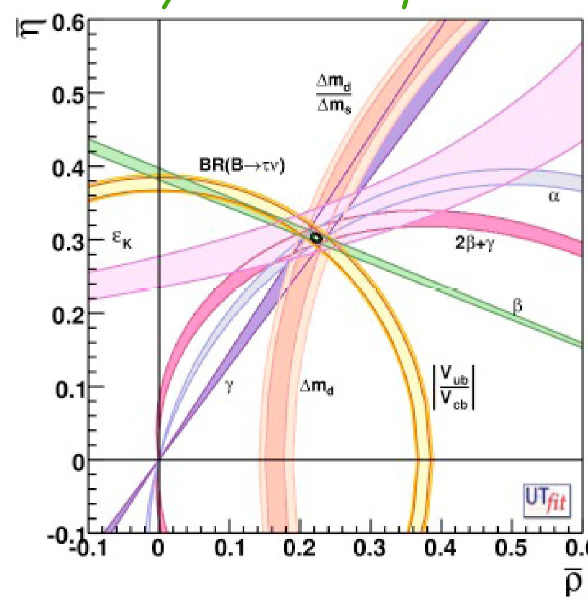


γ is the least well-known angle of the CKM triangle nowadays

Can probe New Physics
(select ρ–η values valid in most of the NP extensions)



Improving the resolution can lead to:
- *consistency with SM prediction*



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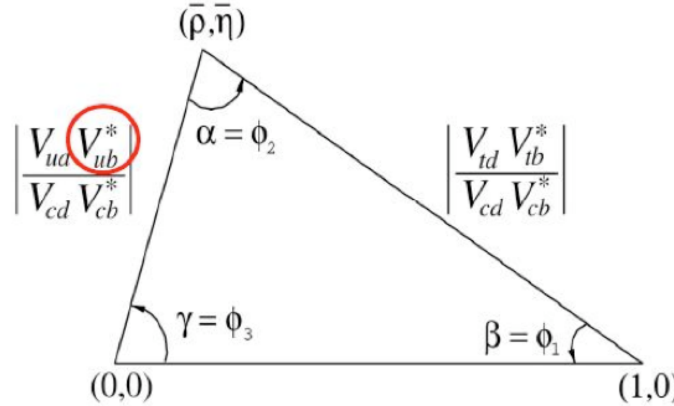

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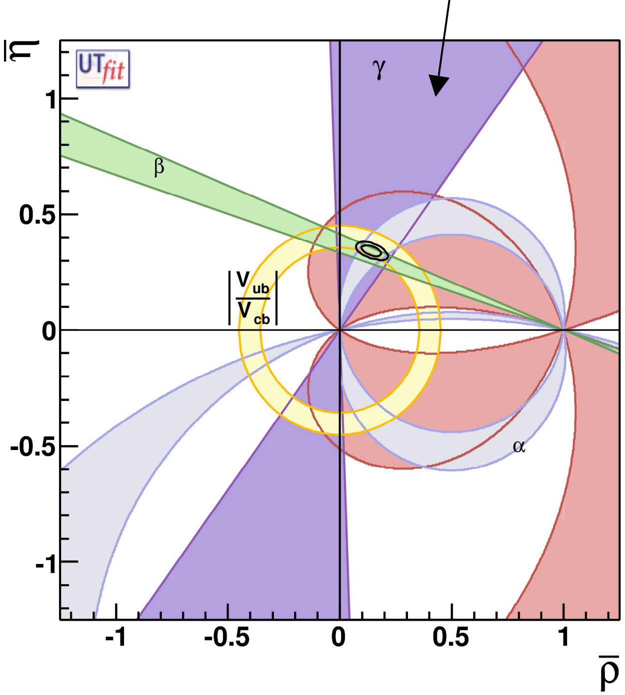
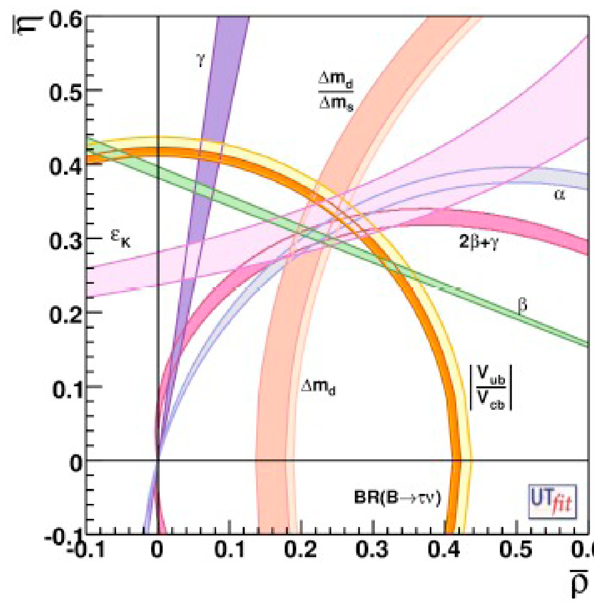


Can probe New Physics
(select $\rho-\eta$ values valid in most of the NP extensions)

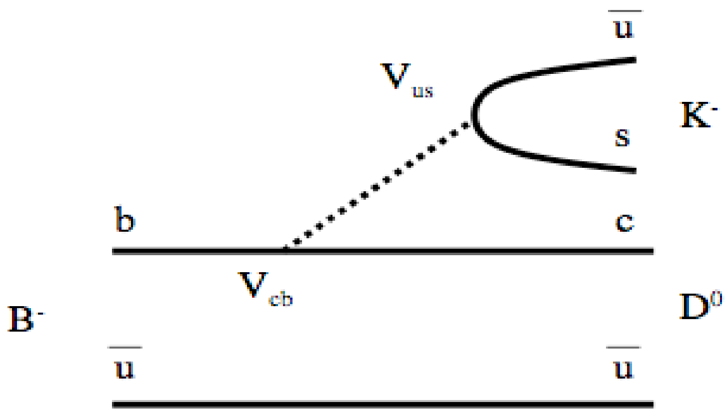
Improving the resolution can lead to:
- *NP scenario*

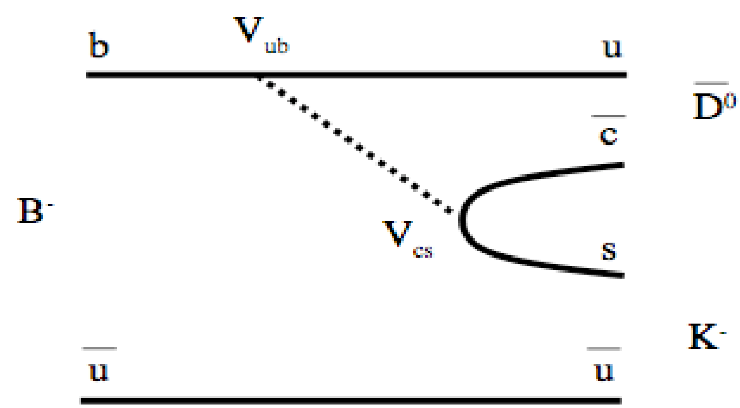


CKM γ angle through $B \to DK$ decays

Use of $B \to DK$ decays is the cleanest way to measure γ:
- tree-level amplitude only
- tiny theoretical uncertanties

γ can be extracted exploiting the interference between the processes $b \to c\bar{u}s$ ($B^- \to D^0 K^-$) and $b \to u\bar{c}s$ ($B^- \to \bar{D}^0 K^-$), when D^0 and $\bar{D}^0$ decay to the same final state





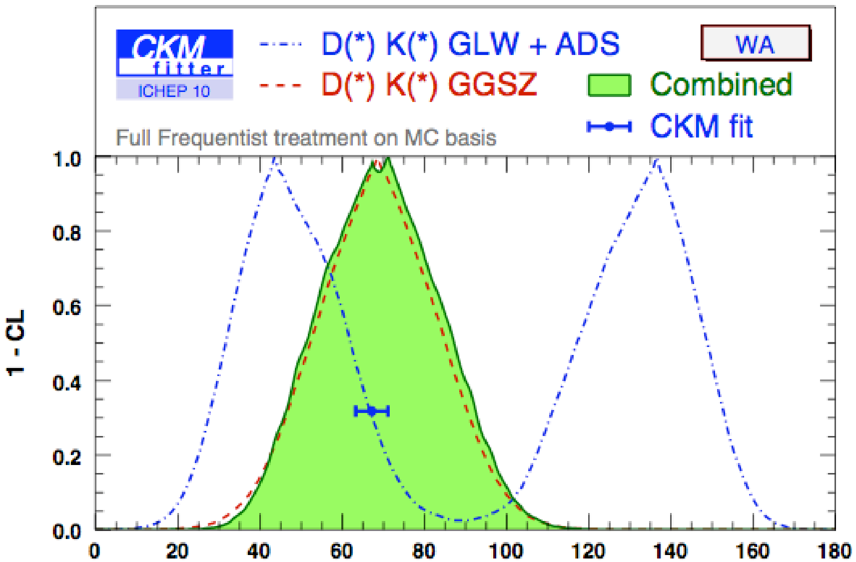
Favored $b \to c$ transition

$A_1 \sim V_{cb}V_{us}^* \sim \lambda^3$

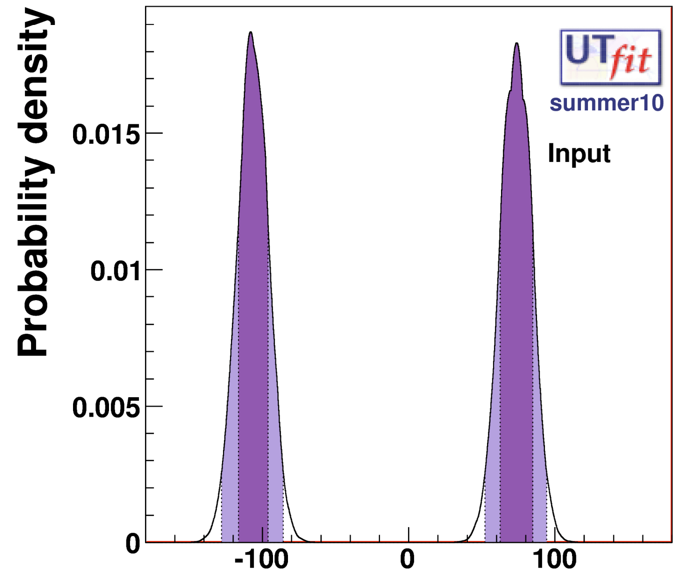
Color suppressed $b \to u$ transition

$A_2 \sim V_{ub}V_{cs}^* \sim \lambda^3 \, r_B \, e^{-i\delta B} \, e^{-i\gamma}$

Current situation for the γ angle measurement using $B^- \to D^0 K^-$



γ(deg) = 71 [+21 -25]



γ(deg) = -106±11 and 74 ± 11

Still large statistical uncertainty

- **GGSZ (Giri-Grossmann-Soffer-Zupan) method** *([PRL78,3257, PRD68,054018])*

that uses the $B^\pm \to D K^\pm$ decays with the D^0 and $\bar{D}^0$ reconstructed into three-body final state. For example the $D^0 \to K^0_s \pi^+ \pi^-$

- **GLW (Gronau-London-Wyler) method** *([PLB253,483 PLB265,172])*

that uses the $B^\pm \to D K^\pm$ decays with D_{CP} decay modes. $D_{CP+} \to \pi^+ \pi^-$, $K^+ K^-$ and $D_{CP-} \to K^0_s \pi^0$, $K^0_s \omega$, $K^0_s \phi$.

- **ADS (Atwood-Dunietz-Soni) method** *([PRL78,3257;PRD63,036005])*

that uses the $B^\pm \to D K^\pm$ decays with D reconstructed in the doubly Cabibbo suppressed $D^0_{DCS} \to K^+ \pi^-$

ADS method

ADS Observables

Direct CP violation in $B \to D_{DCS}K$ modes

- expected large CP asymmetry
- decay suppressed by a factor of $\sim 10^{-3}$ wrt favored
- results have to be combined with other methods to obtain γ measurement

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Observables

$$R_{ADS}(h) = \frac{N(B^- \rightarrow D^0_{DCS}h^-) + N(B^+ \rightarrow D^0_{DCS}h^+)}{N(B^- \rightarrow D^0_{CF}h^-) + N(B^+ \rightarrow D^0_{CF}h^+)}$$

$$\mathcal{A}_{ADS}(h) = \frac{N(B^- \rightarrow D^0_{DCS}h^-) - N(B^+ \rightarrow D^0_{DCS}h^+)}{N(B^- \rightarrow D^0_{DCS}h^-) + N(B^+ \rightarrow D^0_{DCS}h^+)}$$

h = K or π

$D^0_{CF} \rightarrow K^-\pi^+$, $D^0_{DCS} \rightarrow K^+\pi^-$

From theory:

$R_{ADS}(K) = r_D^2 + r_B^2 + 2r_Br_D \cos(\delta_B+\delta_D) \cos\gamma$

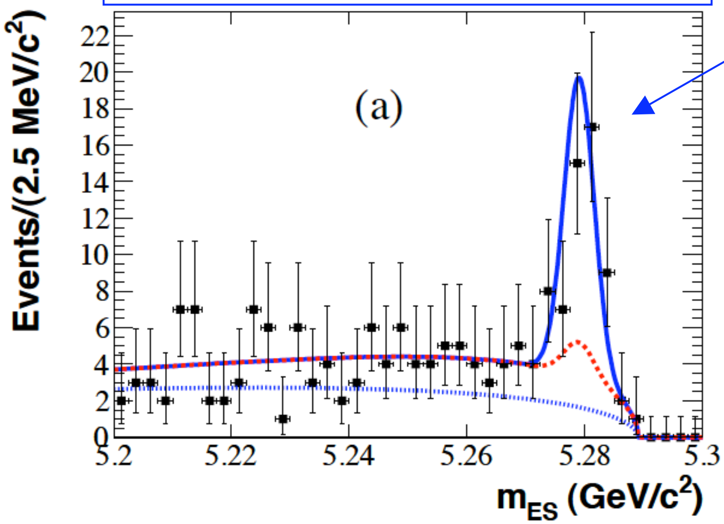
$A_{ADS}(K) = 2r_Br_D \sin(\delta_B+ \delta_D)\sin\gamma/R_{ADS}(K)$

B→DK at b-factories

BaBar ADS result (467M $B\bar{B}$)

(arXiv:1006.4241, accepted by Phys. Rev. D (September 2010))

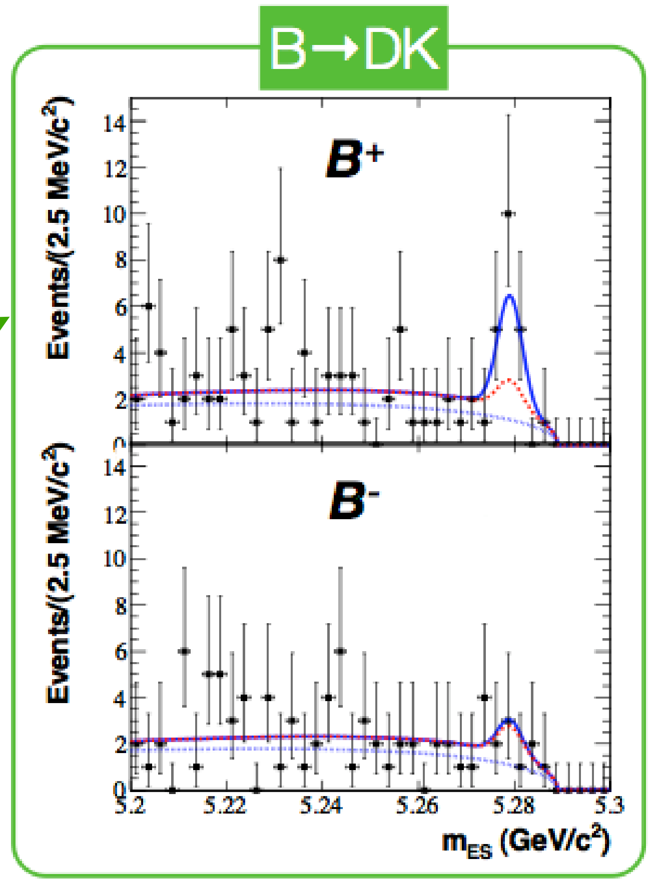
$B \rightarrow D_{DCS}\pi$ reconstruction



~ 80 $B \rightarrow D_{DCS}\pi$ events

$$\mathcal{R}_{D\pi} = (3.3 \pm 0.6 \pm 0.4) \times 10^{-3}$$

$$\mathcal{A}_{D\pi} = 0.03 \pm 0.17 \pm 0.04$$



$B \rightarrow D_{DCS}K$ reconstruction

$$\mathcal{R}_{DK} = (1.1 \pm 0.6 \pm 0.2) \times 10^{-2}$$

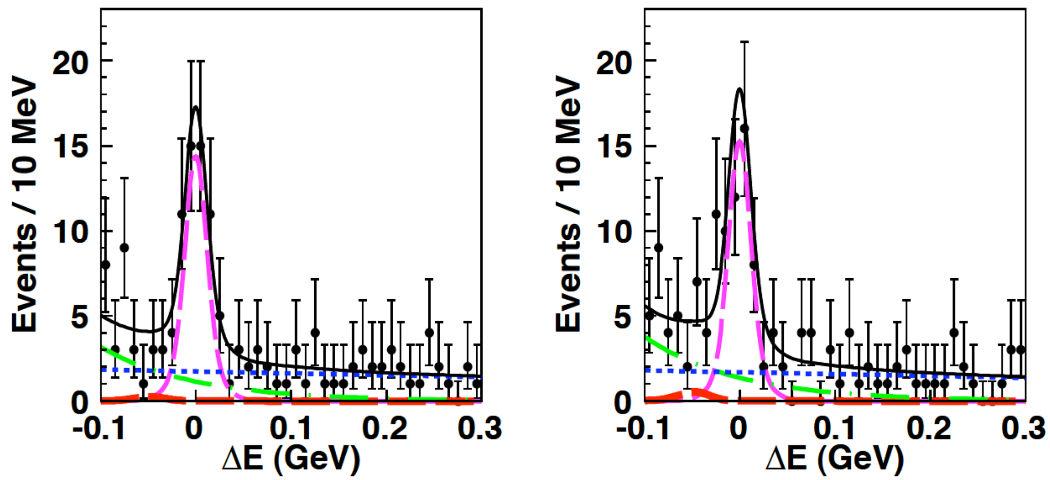
$$\mathcal{A}_{DK} = -0.86 \pm 0.47 \; {}^{+0.12}_{-0.16}$$

~ 20 $B \rightarrow D_{DCS}K$ events,
with a significance of ~2σ

B→DK at b-factories

Belle ADS result (772M $B\bar{B}$)

(arXiv:1103.5951v1, submitted to PRL (March 2011))



B→D$_{DCS}\pi$ reconstruction

~ 165 B→D$_{DCS}\pi$ events

$$\mathcal{R}_{D\pi} = [3.28^{+0.38}_{-0.36}(\text{stat})^{+0.12}_{-0.18}(\text{syst})] \times 10^{-3}$$

$$\mathcal{A}_{D\pi} = -0.04 \pm 0.11(\text{stat})^{+0.02}_{-0.01}(\text{syst})$$

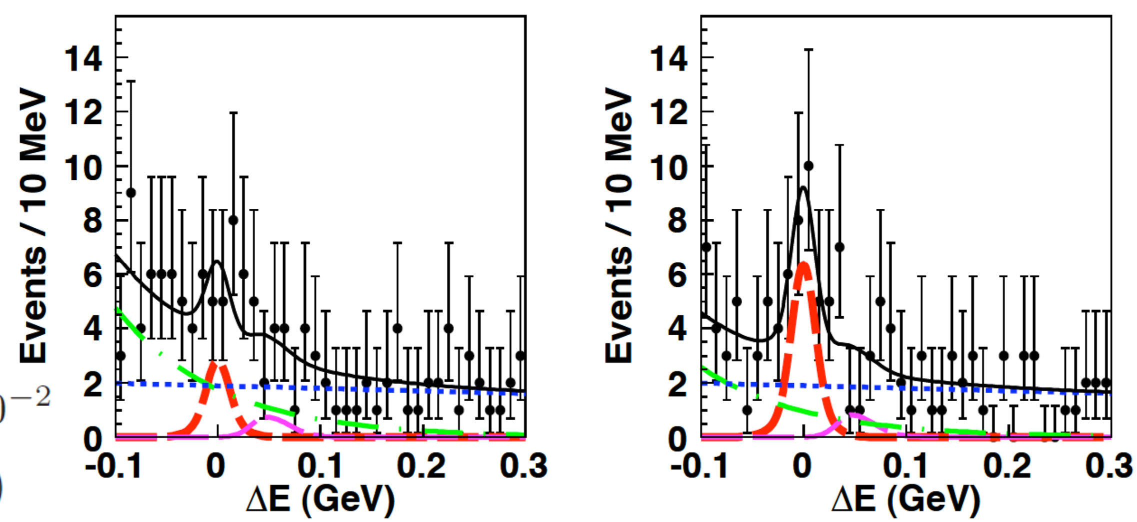
B→D$_{DCS}$K reconstruction

~ 56 B→D$_{DCS}$K events,
Evidence of B→D$_{DCS}$K,
with a significance of 4.1σ

$$\mathcal{R}_{DK} = [1.63^{+0.44}_{-0.41}(\text{stat})^{+0.07}_{-0.13}(\text{syst})] \times 10^{-2}$$

$$\mathcal{A}_{DK} = -0.39^{+0.26}_{-0.28}(\text{stat})^{+0.04}_{-0.03}(\text{syst})$$

DK$^-$ DK$^+$



ADS method at CDF

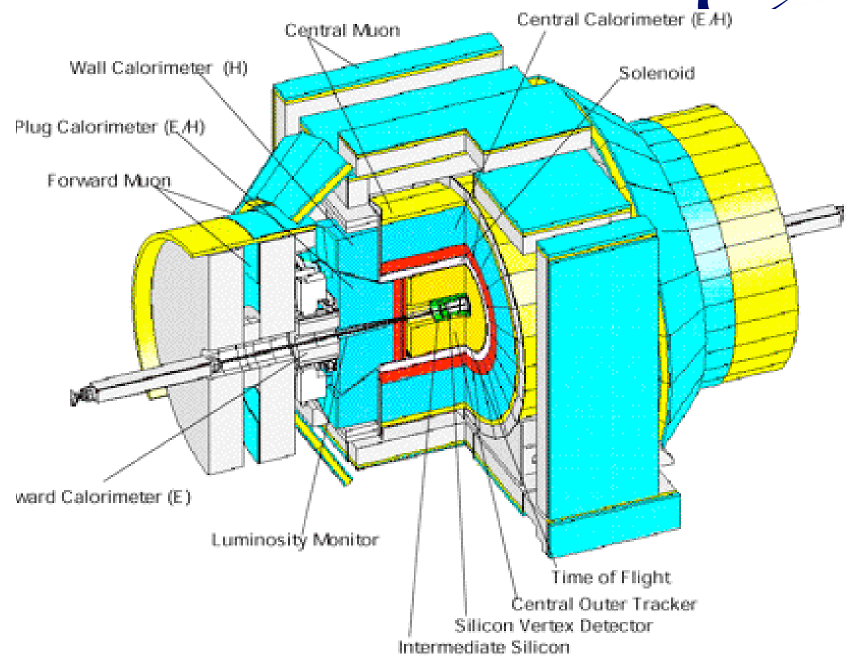
First measurement of A_{ADS} and R_{ADS} at a hadron collider

The CDF II detector

TRACKING system:

- **DRIFT CHAMBER**
96 layers ($|\eta|<1$)

  → 1.5σ π/K separation by dE/dx



- **SILICON TRACKER**
7 layers (1.5-22cm from beam pipe)

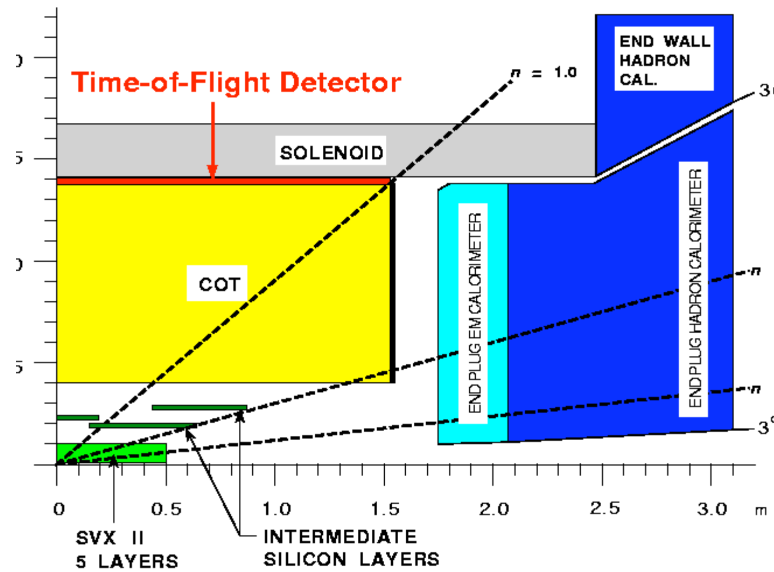
→ I.P. resolution 35 μm at 2 GeV

→ $\sigma(p_T)/p_T^2$ ~ 0.015% (c/GeV)

TRACKING TRIGGER system:

- **Chamber track processor** at L1,
2D tracks in COT, p_T > 1.5 GeV

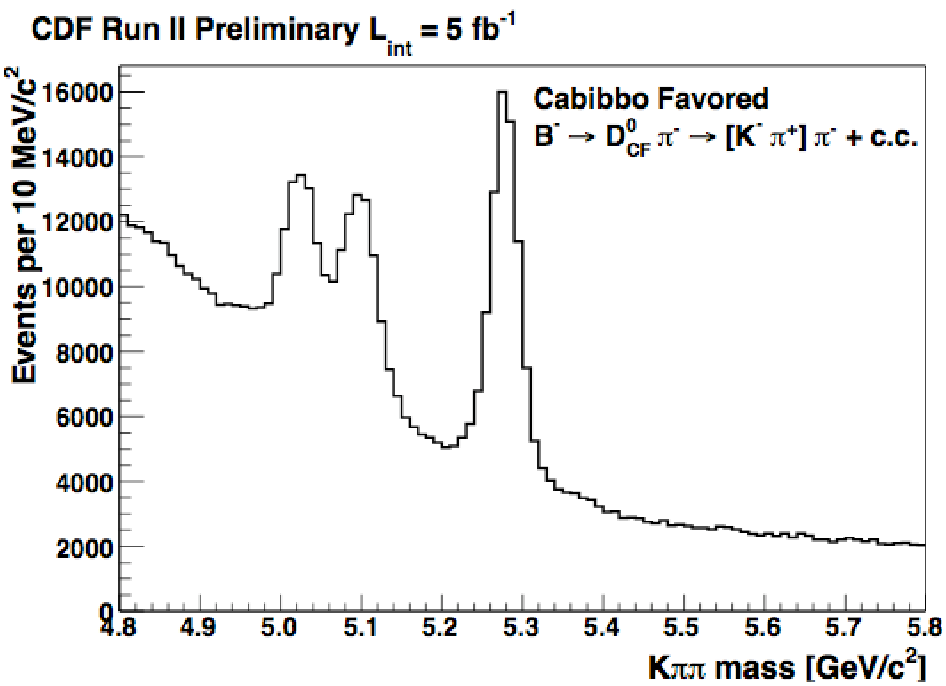
- **Silicon Vertex Trigger** at L2,
2D tracks p_T > 2 GeV,
Impact Parameter measurement (trigger on events containing long lived particles)

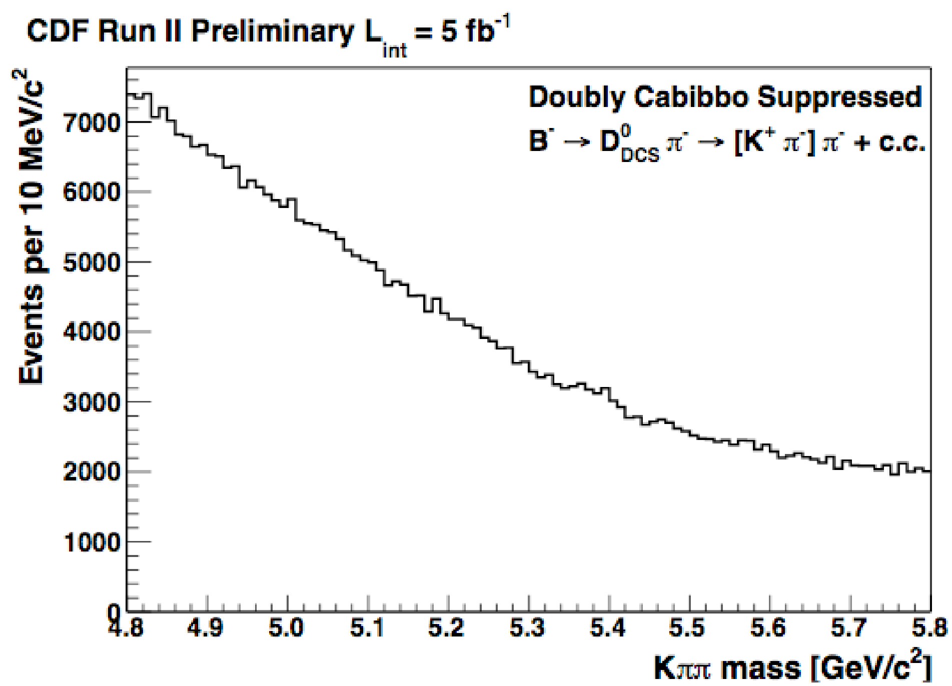


CF and DCS samples ($L = 5fb^{-1}$)

$B^- \to D^0_{CF}\,\pi^- \to [K^-\pi^+]\,\pi^-$

$B^- \to D^0_{DCS}\,\pi^- \to [K^+\pi^-]\,\pi^-$





Cuts optimization → Crucial step toward the DCS modes

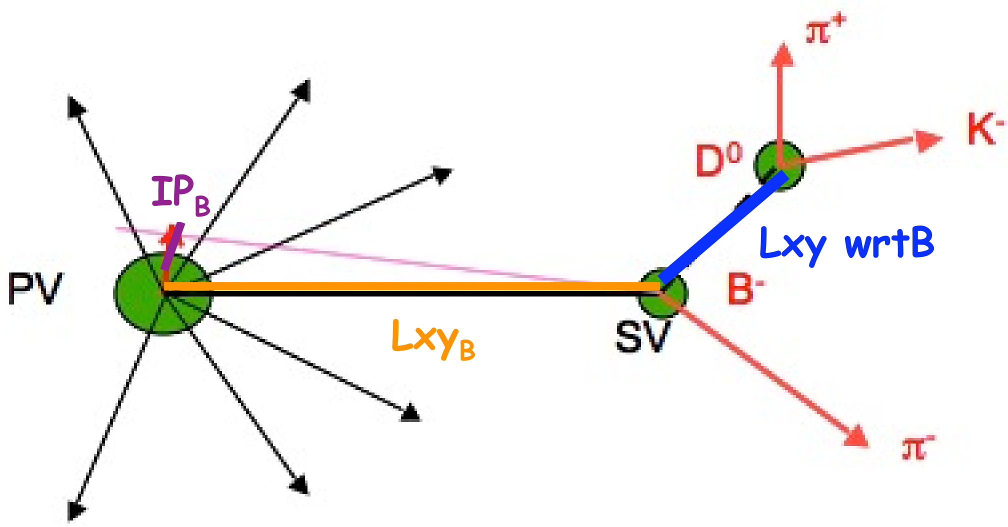
- We directly used the CF sample (not MC) selecting the signal (S) in $\pm 2\sigma$ of $B \to D\pi$ peak and the background (B) in [5.4,5.8] range
- We maximized the quantity $\dfrac{S}{1.5+\sqrt{B}}$ (arXiv:0808063v2)

Optimized selection

D^0 candidate

Cuts on:

- the invariant mass
- angular distribution
- the decay length wrt B to remove $B \rightarrow 3$ body decays
- particle identification of tracks from D^0 to remove $D^0 \rightarrow \pi\pi$ events

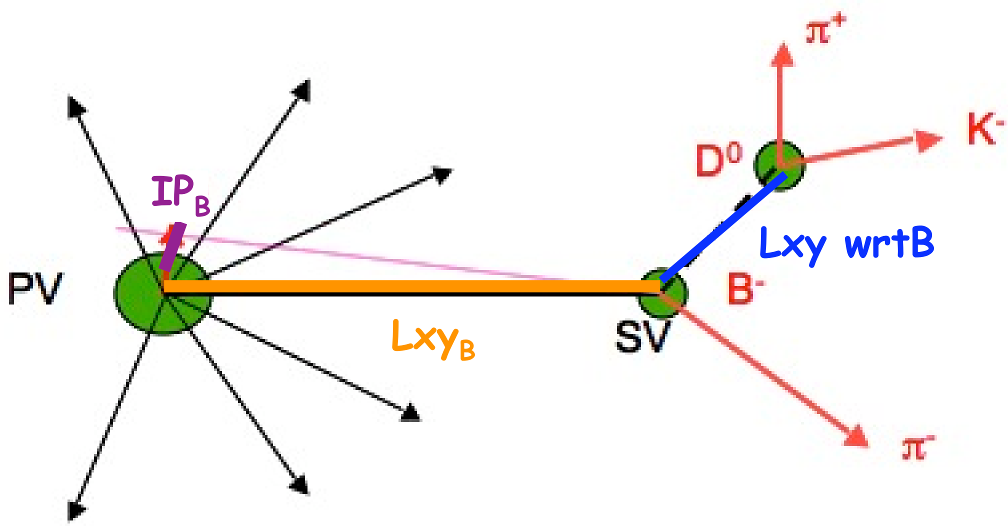


Optimized selection

B candidate

Cuts on:

- decay length wrt primary vertex
- impact parameter
- angle between momentum and decay length



Optimized selection

B candidate

Cuts on:

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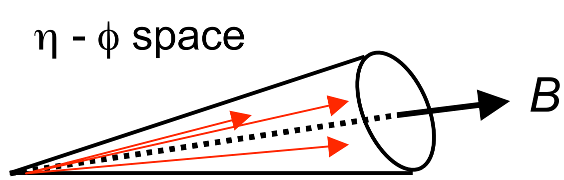
- angle between momentum and decay length

- isolation $I(B) = \frac{p_T(B)}{p_T(B) + \sum_i p_T(i)}$



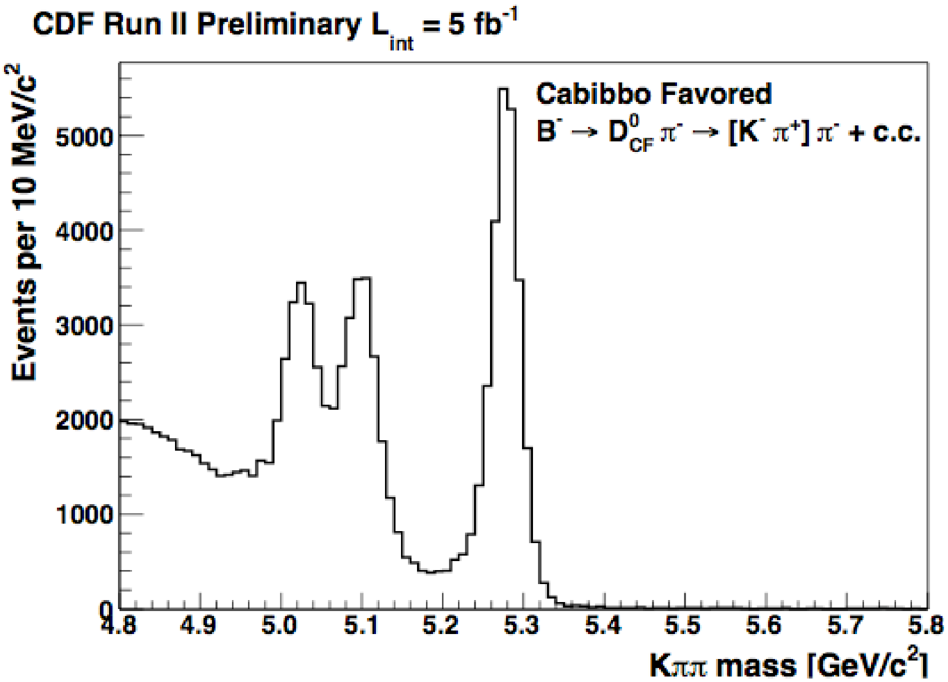
- 3D vertex quality, obtained with the 3D silicon-tracking, to:
  - resolve multiple vertices along the beam direction
  - reject fake tracks.

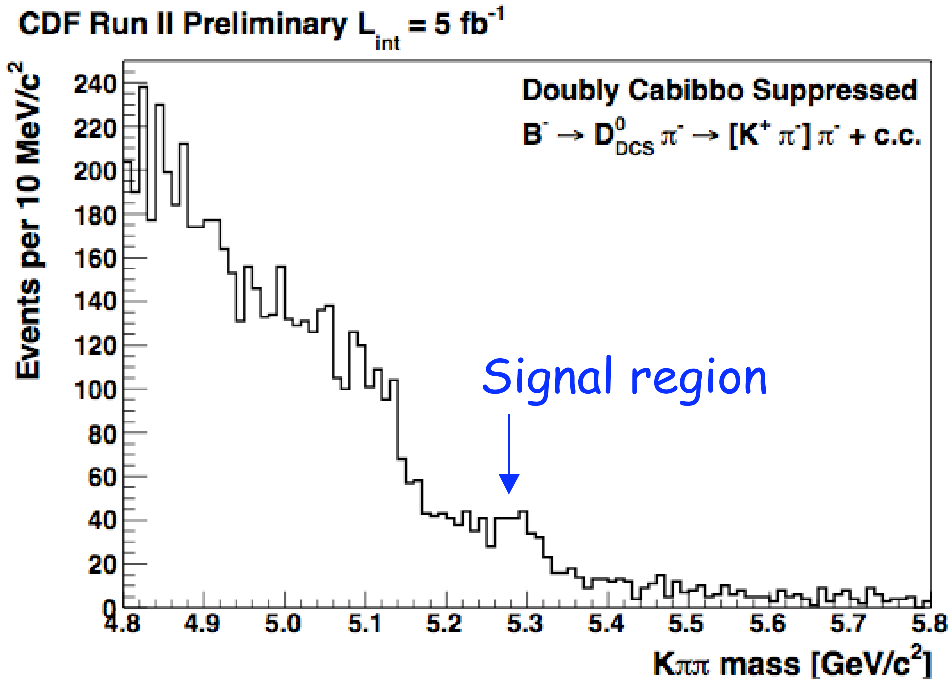
Backg. reduces x2, small inefficiency on signal (<10%).

CF and DCS after cut optimization

$B^- \rightarrow D^0_{CF}\,\pi^- \rightarrow [K^-\,\pi^+]\,\pi^-$

$B^- \rightarrow D^0_{DCS}\,\pi^- \rightarrow [K^+\,\pi^-]\,\pi^-$





The combinatorial background is almost reduced to zero and an excess of events appears in the signal region of the DCS sample.

Fit procedure

Use of an unbinned maximum likelihood fit (combined on CF and DCS modes) to separate signals contribution.

$$\mathcal{L} = \prod_{k}^{Nevents} \left[f_{sig}\mathcal{F}_{sig} + (1 - f_{sig}) \cdot \mathcal{F}_{back} \right]$$

$\mathcal{F}_{sig}$ = sum of $B^- \to D^0 \pi^-$, $B^- \to D^{*0} \pi^-$ and $B^- \to D^0 K^-$ likelihood

$\mathcal{F}_{back}$ = sum of combinatorial and physics background likelihood

We used:

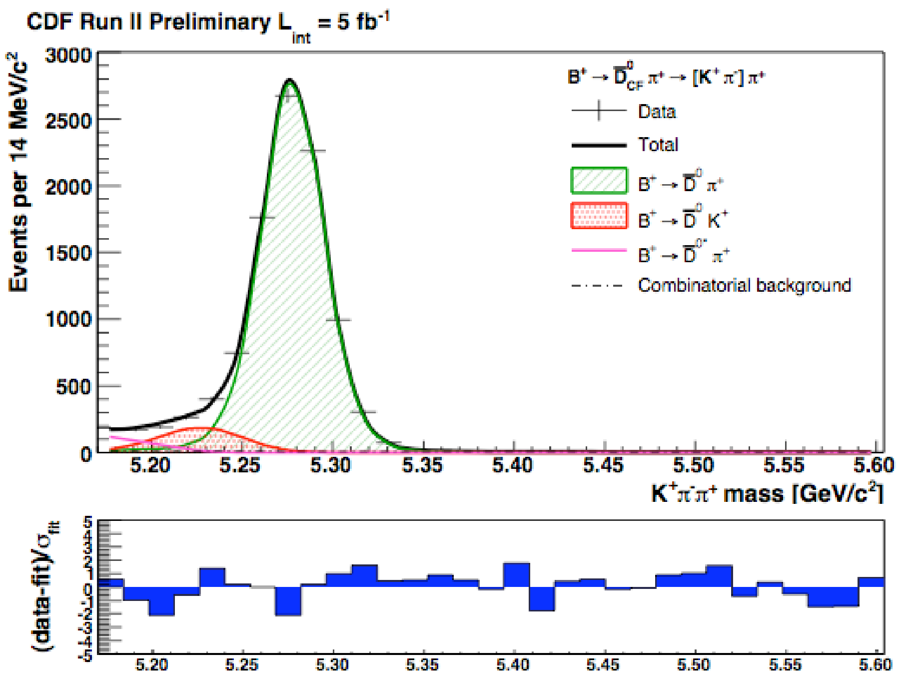
- mass information
- particle identification (dE/dx with K-π separation: 1.5 σ for p > 2 GeV/c)

Common parameters between CF and DCS:

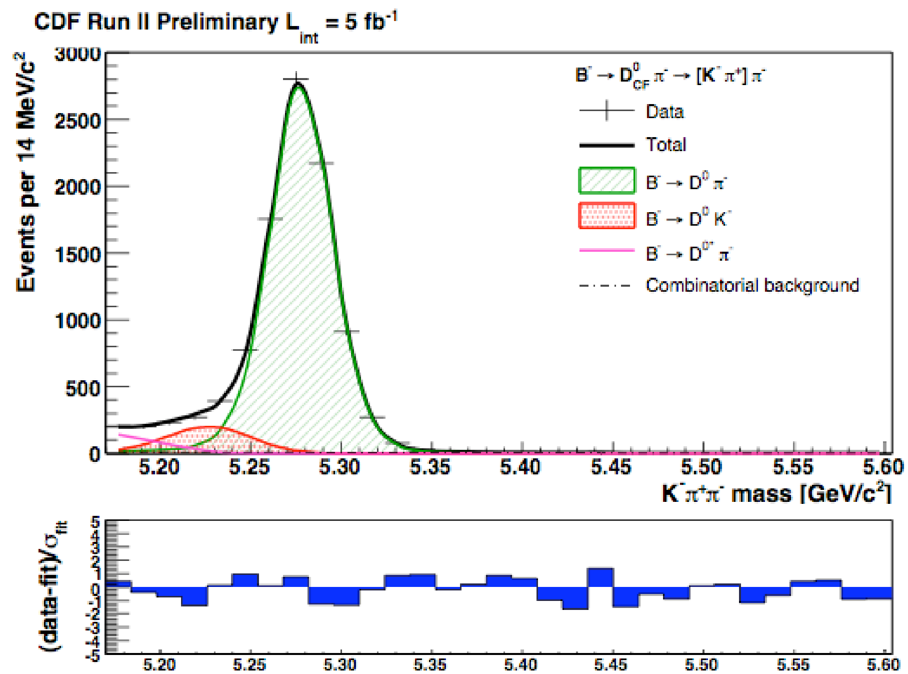
- ratio between $N(B^- \to D^{*0} \pi^-) / N(B^- \to D^0 \pi^-)$
- combinatorial background pdf

Results: CF reconstruction

$B^+ \rightarrow \bar{D}^0_{CF}\ \pi^+ \rightarrow [K^-\ \pi^+]\ \pi^+$



$B^- \rightarrow D^0_{CF}\ \pi^- \rightarrow [K^+\ \pi^-]\ \pi^-$



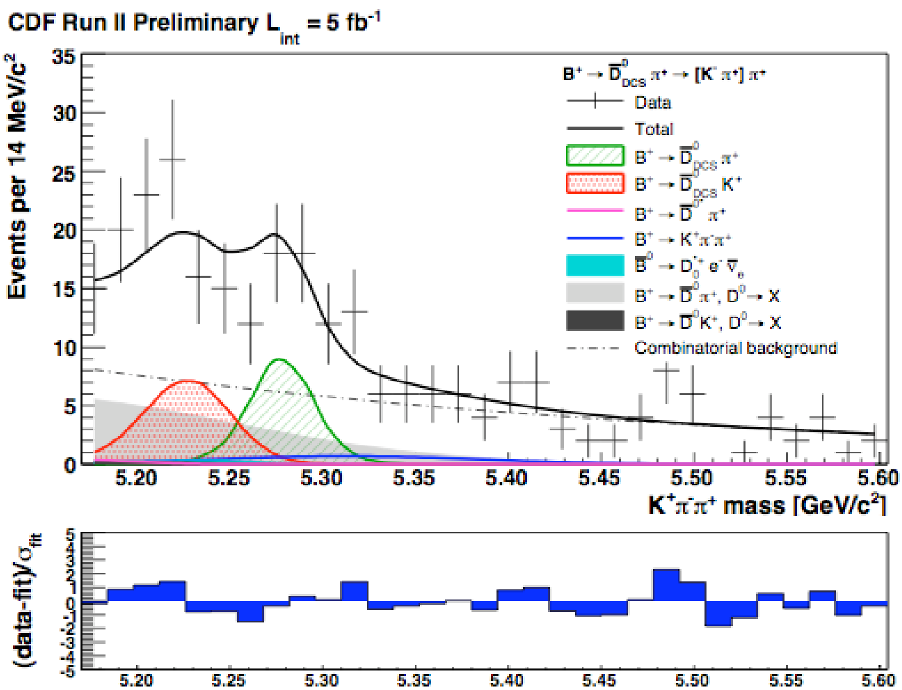
Yield ($B \rightarrow D_{CF}K$) = 1513 ± 68 (5 fb^{-1})

Yield ($B \rightarrow D_{CF}\pi$) = 17677 ± 146 (5 fb^{-1})

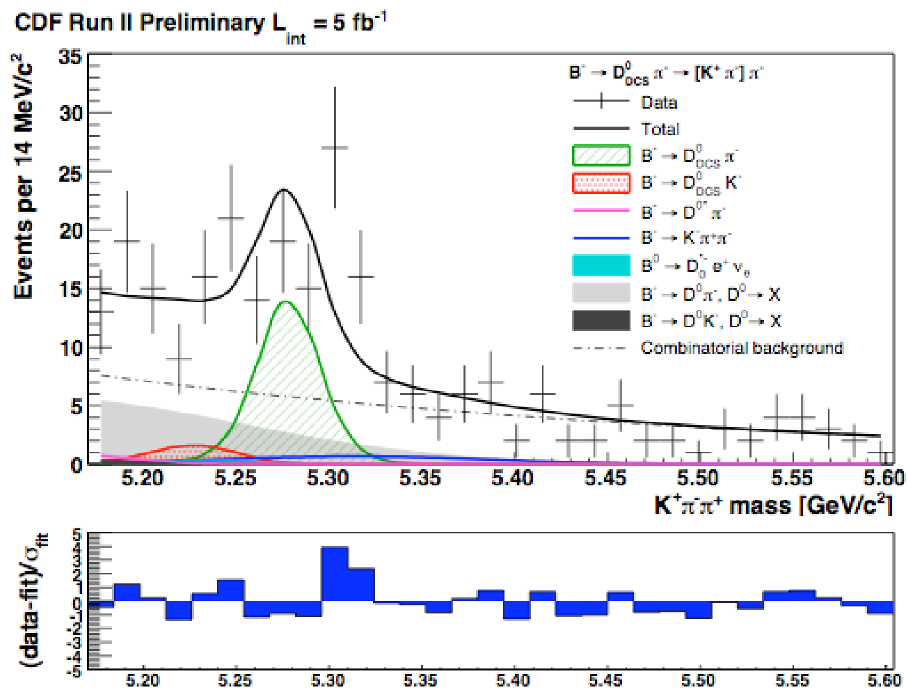
Results: DCS reconstruction

First reconstruction of DCS signals at a hadron collider.

$B^+ \to \bar{D}^0_{DCS}\,\pi^+ \to [K^- \pi^+]\,\pi^+$



$B^- \to D^0_{DCS}\,\pi^- \to [K^+ \pi^-]\,\pi^-$



Yield ($B \to D_{DCS}K$) = 34 ± 14 (5 fb^{-1})
Yield ($B \to D_{DCS}\pi$) = 73 ± 16 (5 fb^{-1})

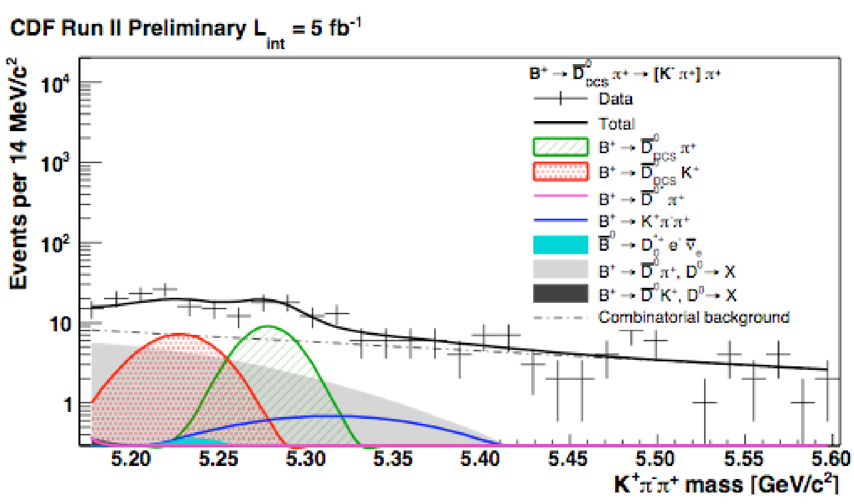
Significance for all DCS signals ($D_{DCS}\pi$ + $D_{DCS}K$) > 5 σ

Results: physics background

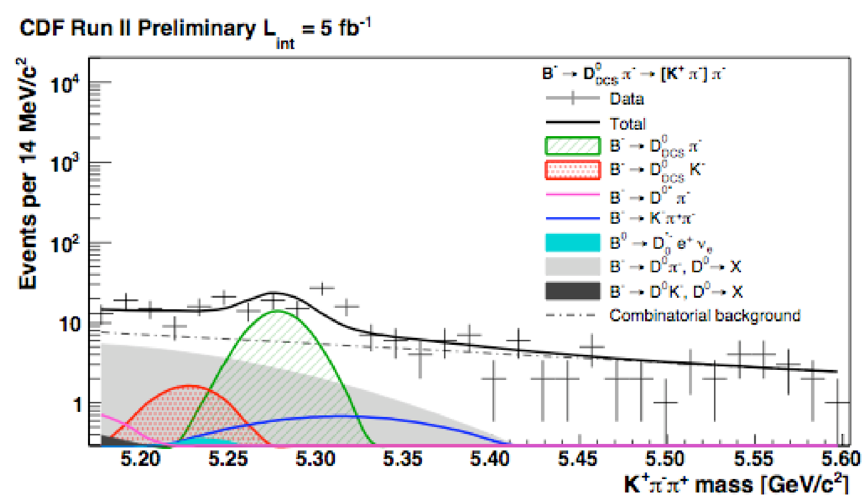
Physics background for DCS:

Decay	Yield
$B^- \to D^{0*} \pi^-$, $D^{0*} \to D^0 \gamma / \pi^0$	3 ± 3
$B^- \to D^0 \pi^-$, $D^0 \to X$	90 ± 13
$B^- \to D^0 K^-$, $D^0 \to X$	4 ± 3
$B^- \to K^- \pi^+ \pi^-$	18 ± 4
$B^0 \to D_0^{*-} e^+ \nu_e$	4 ± 3

$B^+ \to \bar{D}^0_{DCS} \pi^+ \to [K^- \pi^+] \pi^+$



$B^- \to D^0_{DCS} \pi^- \to [K^+ \pi^-] \pi^-$



Results: the observables

First measurement of A_{ADS} and R_{ADS} at a hadron collider.

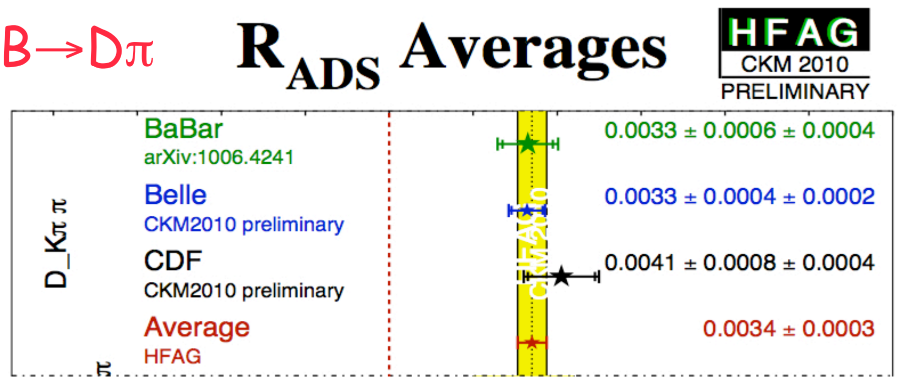
$$\boxed{\begin{aligned} R_{ADS}(\pi) &= 0.0041 \pm 0.0008(stat) \pm 0.0004(syst) \\ A_{ADS}(\pi) &= 0.22 \pm 0.18(stat) \pm 0.06(syst) \\ R_{ADS}(K) &= 0.0225 \pm 0.0084(stat) \pm 0.0079(syst) \\ A_{ADS}(K) &= -0.63 \pm 0.40(stat) \pm 0.23(syst) \end{aligned}}$$

(CDF public note 10309)

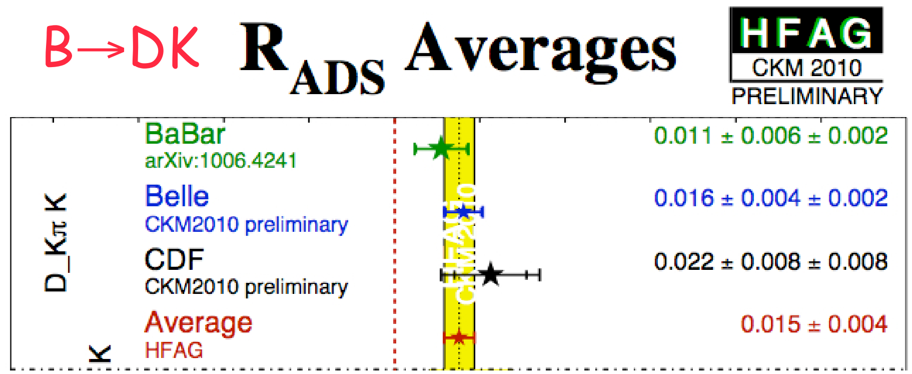
Summary of results

The results are in agreement and compatible with B-factories

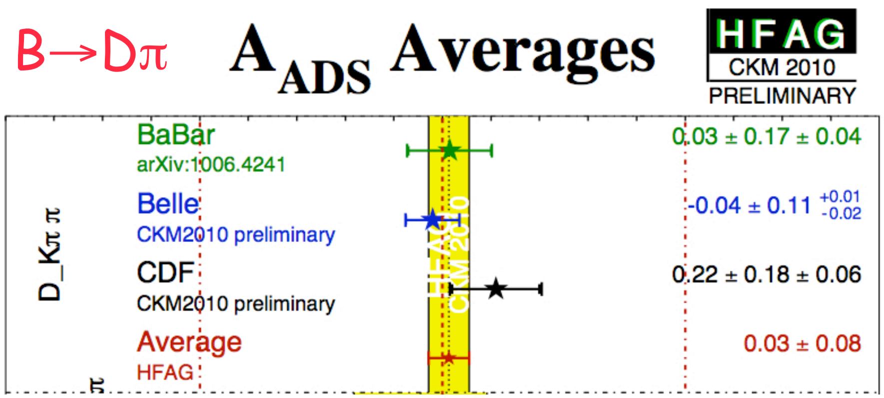
B→Dπ



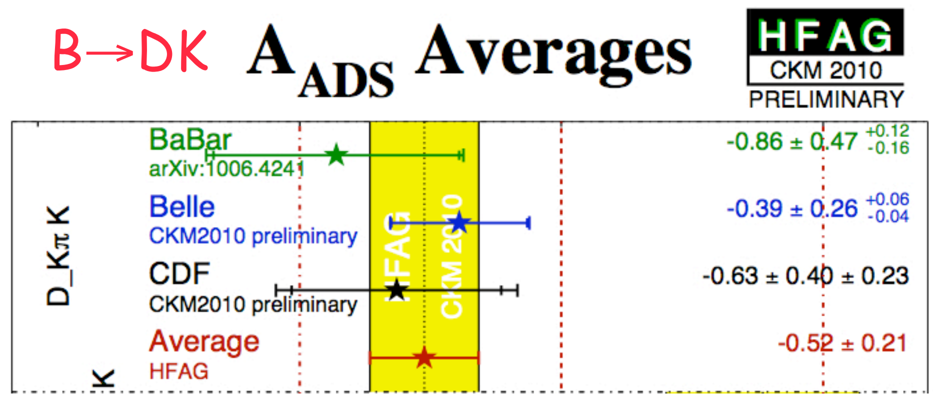
B→DK



B→Dπ



B→DK



CDF program on γ

The ADS measurement belongs to a *broader program of CDF for measuring γ from trees.*

Recently published the **GLW measurement** using 1 fb^{-1} of data *(Phys.Rev.D81:031105,2010)*

The GLW method

- Direct CP violation in $B \to D_{CP}K$ modes ($D_{CP+} \to \pi^+ \pi^-$, $K^+ K^-$ and $D_{CP-} \to K^0_s \pi^0$, $K^0_s \omega$, $K^0_s \phi$.)
- very clean method
- small asymmetry, sensitivity to γ proportional to r_B

The observables

$$R_{CP\pm} = \frac{\Gamma(B^- \to D^0_{CP\pm}K^-) + \Gamma(B^+ \to D^0_{CP\pm}K^+)}{[\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to D^0 K^+)]/2}$$

$$A_{CP\pm} = \frac{\Gamma(B^- \to D^0_{CP\pm}K^-) - \Gamma(B^+ \to D^0_{CP\pm}K^+)}{\Gamma(B^- \to D^0_{CP\pm}K^-) + \Gamma(B^+ \to D^0_{CP\pm}K^+)}$$

From theory:

$R_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\gamma$

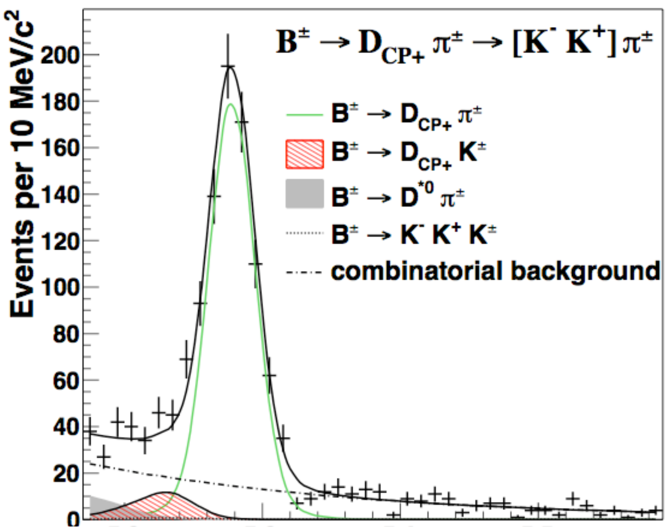
$A_{CP\pm} = 2r_B \sin\delta_B \sin\gamma / R_{CP\pm}$

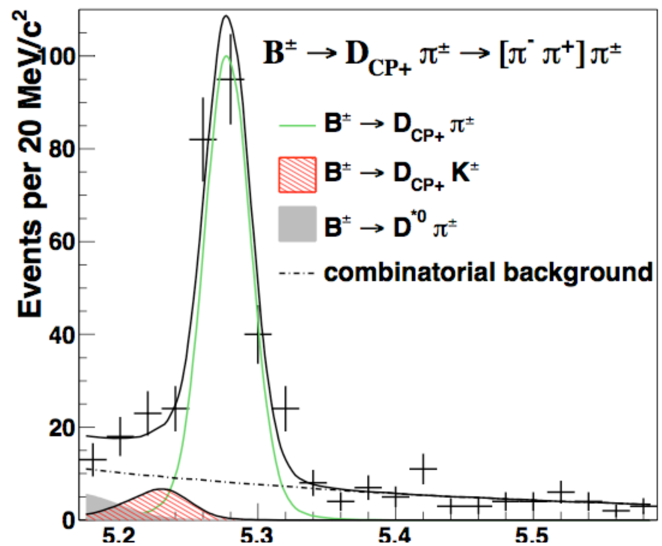
3 independent equations ($A_{CP+}R_{CP+} = -A_{CP-}R_{CP-}$) and 3 unknowns ($r_B$, γ, δ_B)

CP+ modes results

D mode	$B^+ \to D\pi^+$	$B^- \to D\pi^-$	$B^+ \to DK^+$	$B^- \to DK^-$
$K^-\pi^+$	3769 ± 68	3763 ± 68	250 ± 26	266 ± 27
K^+K^-	381 ± 25	399 ± 26	22 ± 8	49 ± 11
$\pi^+\pi^-$	101 ± 13	117 ± 14	6 ± 6	14 ± 6

Yield ($B \to D_{CP+}K$) ~ 90 (1 fb^{-1})





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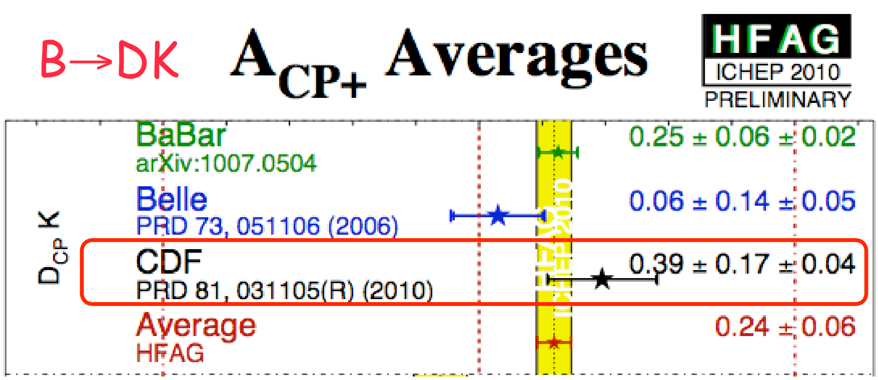

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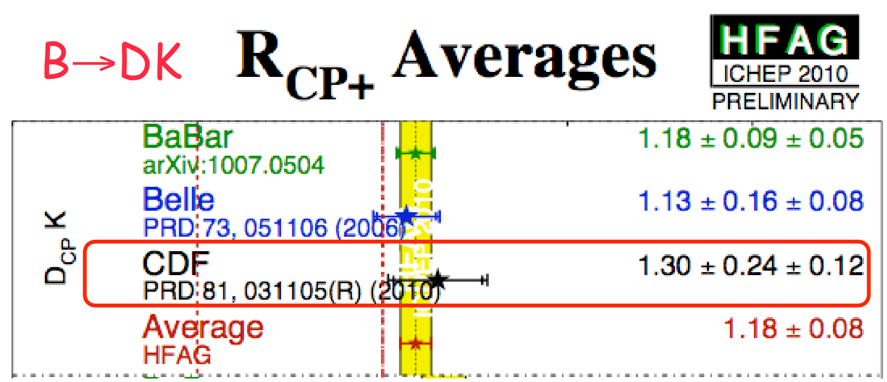


Conclusions

- CDF performed:
  - first measurement of $\mathbf{A_{ADS}}$ **and** $\mathbf{R_{ADS}}$ at a hadron collider using 5 fb^{-1}.
    - Significance of DCS signals ($D_{DCS}\,\pi$ + $D_{DCS}\,K$) > 5σ
  - first measurement of $\mathbf{A_{CP+}}$ **and** $\mathbf{R_{CP+}}$ at a hadron collider using 1 fb^{-1}.

- Not only demonstrated the **capability** of hadron collider with **B to charm decays**, but we even get competitive results with B-factories

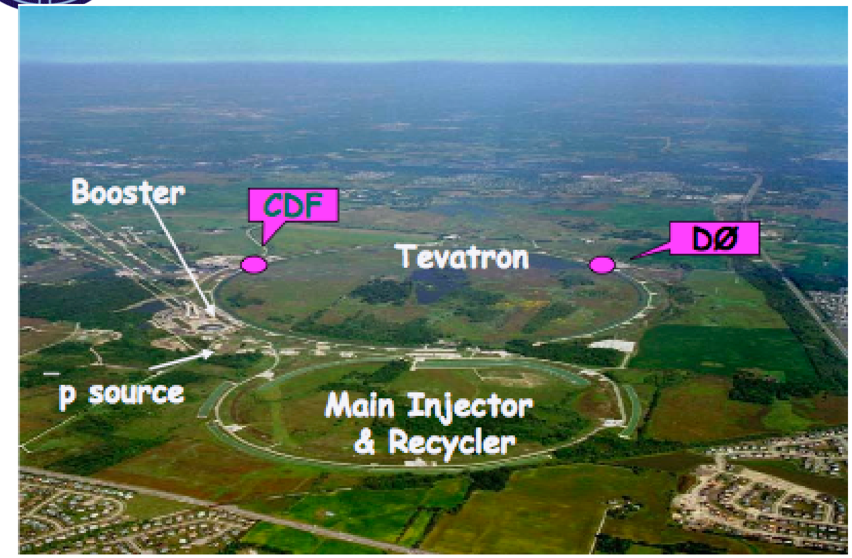
- In a few months we will have a doubled dataset.

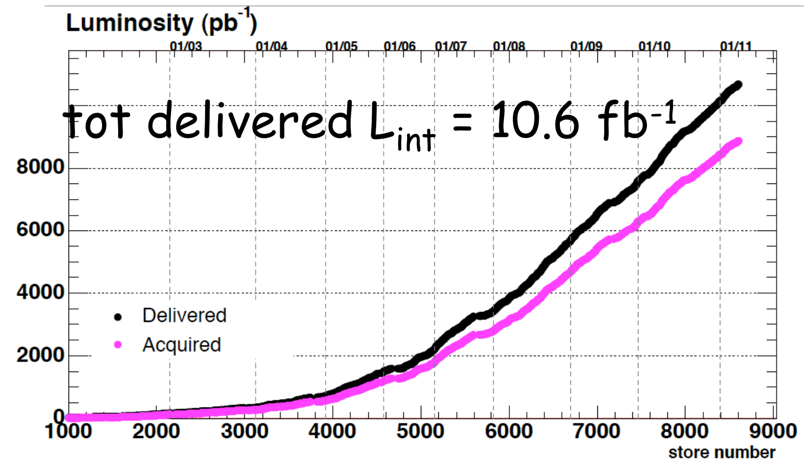
BACK-UP

The Tevatron

Good performances on Run II:

- peak L_{inst} = 3.5-4 $10^{32} cm^{-2} s^{-1}$
- delivering 2.5 fb^{-1}/year

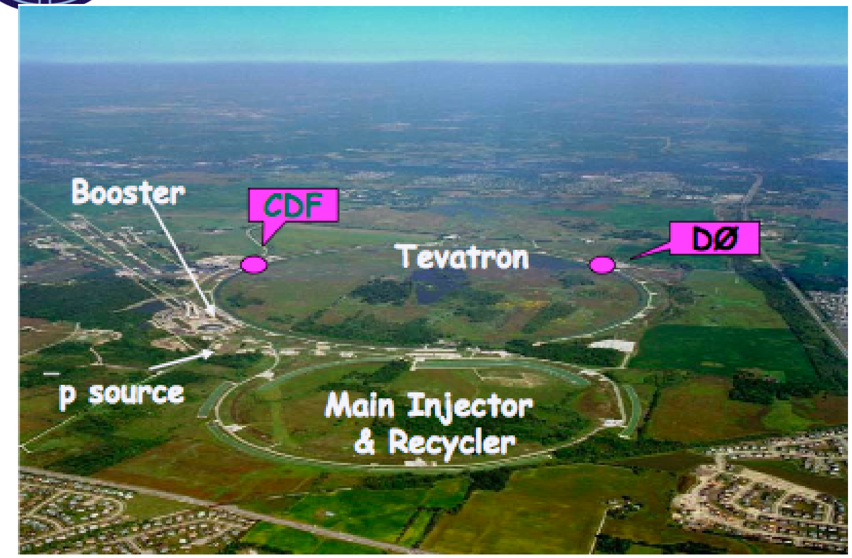




Tevatron is great for rare B decay searches:

- **Large *b* production cross section**
  (x1000 times larger than e^+e^- B factories)
- ***All* B species** are produced (B^0, B^+, B_s, Λ_b…)

The Tevatron



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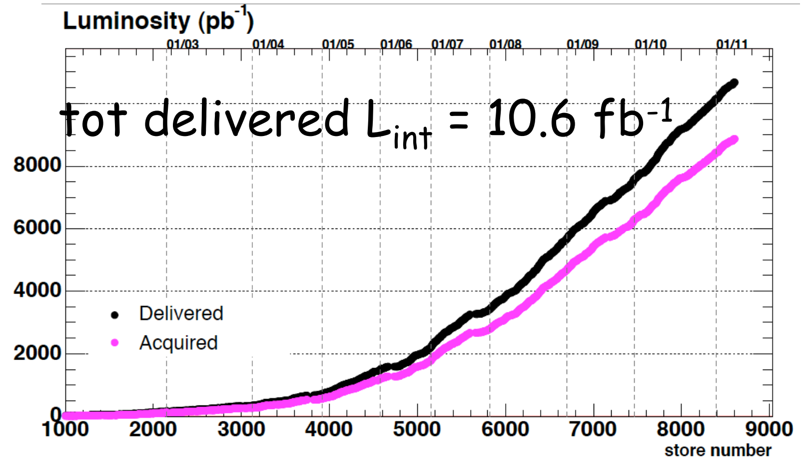

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- ***Large b* production cross section**
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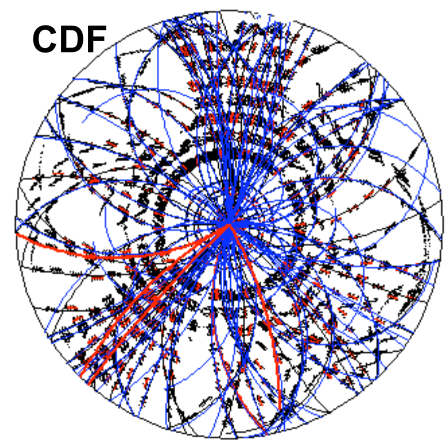
But:

- The **total** inelastic **x-section** is a factor **10^3** larger than $\sigma(b\bar{b})$
- The **BRs** of rare b-hadron decays are **$O(10^{-6})$** or lower

Interesting events must be extracted from a high track multiplicity environment

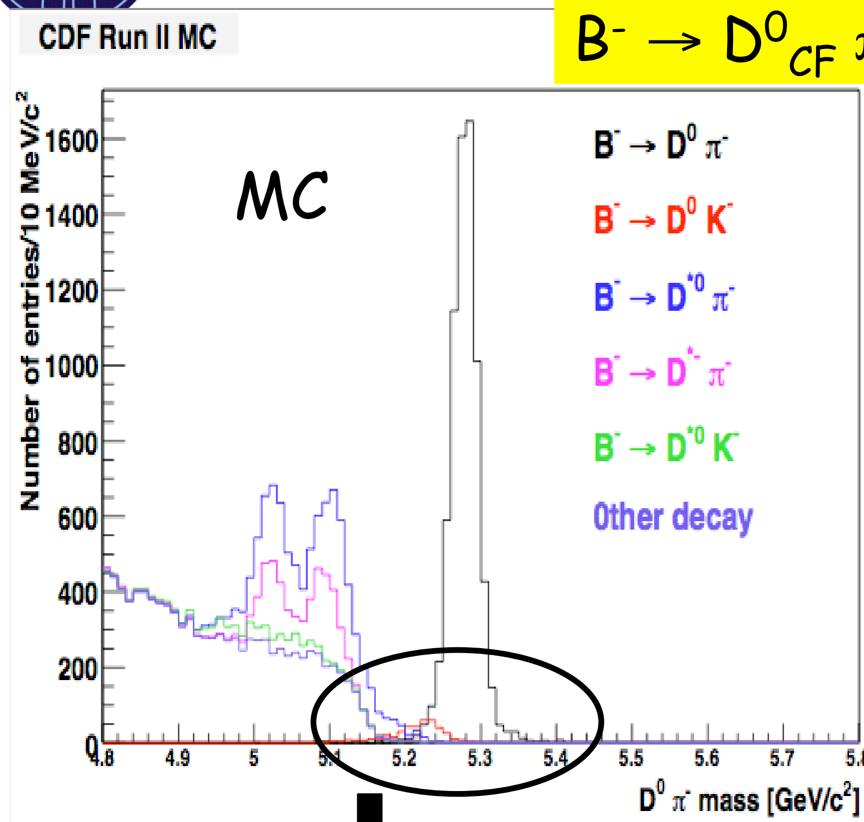


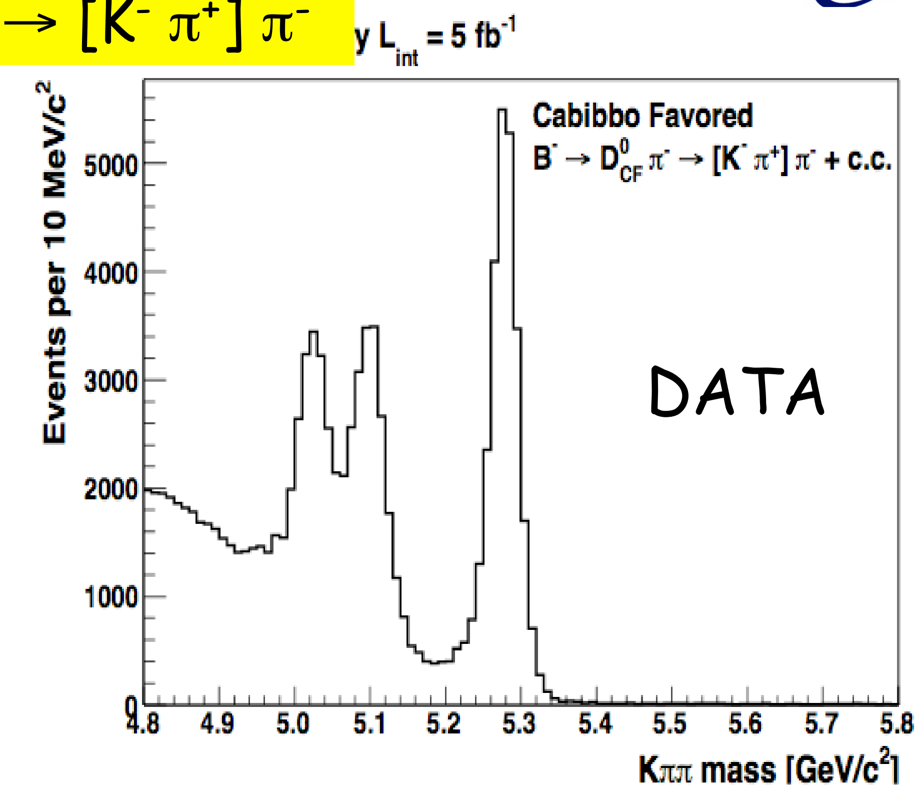
Detectors need to have:

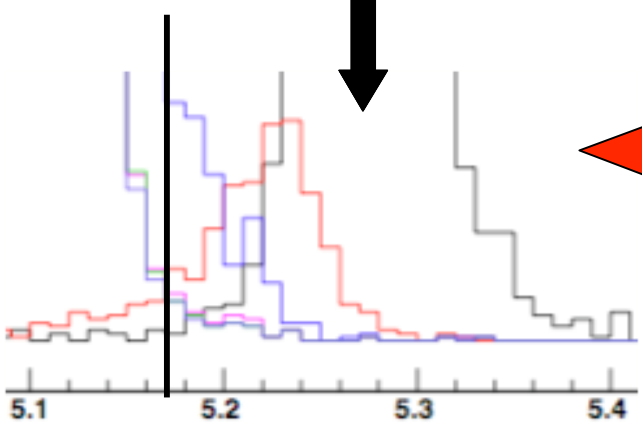
- Very **good tracking** and vertex resolution and **highly selective trigger**

Separating DK from other modes

$B^- \to D^0_{CF}\,\pi^- \to [K^-\pi^+]\,\pi^-$





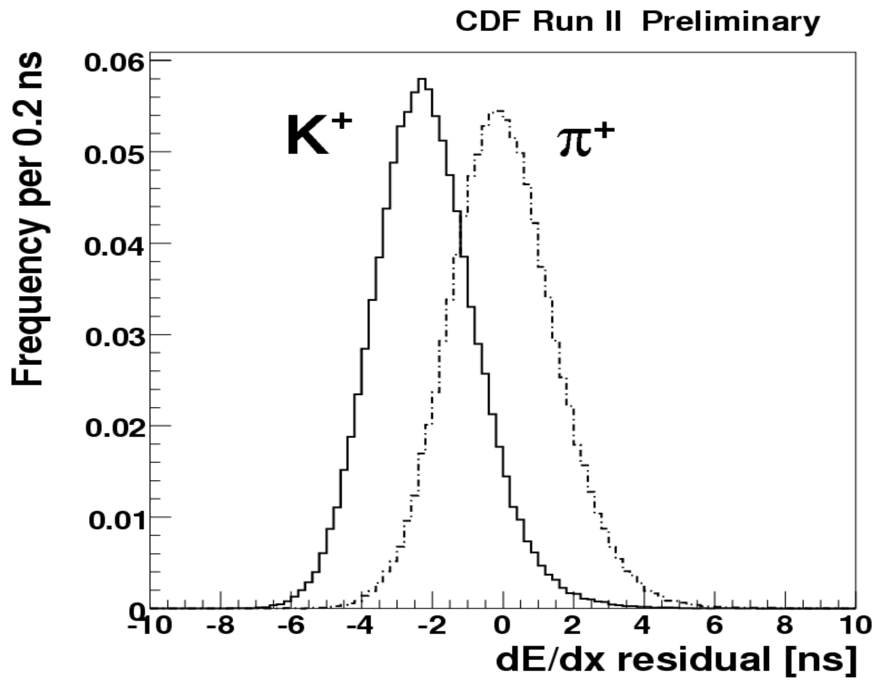


To reject most of the physical backgrounds, narrow fit windows [5.17,6.5]

The only significant physics backgrounds are $B^- \to D^0\pi^-$ and $B^- \to D^{0*}\pi^-$

Separation by Particle ID

Implementation of a Likelihood FIT using masses and particle identification (dE/dx) information to determine the signal composition



K - π separation: 1.5 σ for $p > 2$ GeV/c

ADS: Systematics

Source	$R_{ADS}(\pi)$	$R_{ADS}(K)$	$A_{ADS}(\pi)$	$A_{ADS}(K)$
dE/dx	0.0001	0.0050	0.0560	0.070
combinatorial background	0.0003	0.0037	0.0073	0.153
$B^- \to [X]_D \pi^-$ shape	0.0002	0.0025	0.0067	0.057
$B^- \to [X]_D K^-$ shape	-	0.0001	0.0003	0.003
$B^- \to K^- \pi^+ \pi^-$ shape	0.0001	0.0004	0.0049	0.009
$B^0 \to D_0^{*-} e^+ \nu_e$ shape	-	0.0003	0.0020	0.007
$B^- \to D^{*0} \pi^-$ shape	-	0.0005	0.0009	0.013
efficiency	-	0.0001	-	0.003
bias	0.0001	0.0042	0.0159	0.148
Total	**0.0004**	**0.0079**	**0.059**	**0.232**

- dE/dx we varied the shapes of the PID pdfs

- Combinatorial and physics background: we varied the shapes used in the fit

- efficiency of K+/K- reconstruction

- Fit bias: checked with pseudo-experiments MC

ADS: Likelihood

$$\mathcal{L} = \mathcal{L}_{CF+} \cdot \mathcal{L}_{CF-} \cdot \mathcal{L}_{DCS+} \cdot \mathcal{L}_{DCS-}$$

$$\mathcal{L}_{CF+} = \prod_{i}^{Nevents} \Big[(1-b_{CF+}) \cdot \Big(f_{\pi}^{CF+} \cdot pdf_{\pi}(M,ID) + \mathbf{c}^{+} \cdot f_{\pi}^{CF+} \cdot pdf_{D*}(M,ID) + \\ + \Big(1 - f_{\pi}^{CF+} - \mathbf{c}^{+} \cdot f_{\pi}^{CF+}\Big) \cdot pdf_{K}(M,ID)\Big) + b_{CF+} \cdot pdf_{comb}(M,ID)\Big]$$

$$\mathcal{L}_{DCS+} = \prod_{i}^{Nevents} \Big[(1-b_{DCS+}) \cdot \Big(f_{\pi}^{DCS+} \cdot pdf_{\pi}(M,ID) + \mathbf{c}^{+} \cdot f_{\pi}^{DCS+} \cdot pdf_{D*}(M,ID) + \\ + \Big(1 - f_{\pi}^{DCS+} - \mathbf{c}^{+} \cdot f_{\pi}^{DCS+}\Big) \cdot pdf_{K}(M,ID)\Big) + \\ + b_{DCS+} \cdot \Big(f_{[X]\pi}^{+} \cdot pdf_{[X]\pi}(M,ID) + f_{[X]K}^{+} \cdot pdf_{[X]K} + f_{K\pi\pi}^{+} \cdot pdf_{K\pi\pi}(M,ID) + \\ f_{B^0}^{+} \cdot pdf_{B^0}(M,ID) + (1 - f_{[X]\pi}^{+} - f_{[X]K}^{+} - f_{K\pi\pi}^{+} - f_{B^0}^{+}) \cdot pdf_{comb}(M,ID)\Big)\Big]$$

Analogous expressions for negative charges

- $pdf_i(M,ID) = pdf_i(M) * pdf_i(ID)$
- Fitted parameters
  - $b_{CF,\ DCS}$ = background fraction for CF and DCS
  - $f_{\pi,\ CF,\ DCS}$ = B->D^0 π fraction for CF and DCS signal
  - $c = f_{D*} / f_{\pi}$ (equal for CF and DCS)
  - $f_{[X]\pi}$ = fraction of B->D^0 π, D^0->X in DCS reconstruction (constrained from MC)
  - $f_{[X]K}$ = fraction of B->D^0K, D^0->X in DCS reconstruction (constrained from MC)
  - $f_{K\pi\pi}$ = fraction of B->K- π+ π- in DCS reconstruction (constrained from MC)
  - f_{B0} = fraction of B^0->D*- e ν in DCS reconstruction (constrained from MC)